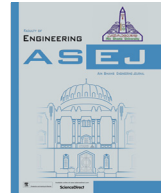




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Numerical simulation of the aerodynamic performance of a novel micro-aerial vehicle mimicking a locust

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ABSTRACT

This paper describes the design, micro-fabrication and testing of a novel Micro-Aerial Vehicle (MAV) that mimicking a real locust. Actual parameters of locust insect are used to create a micro-scale MAV that can replace the traditional types that mimicking dragonfly and birds. Based on the obtained results, the novel MAV crucial parameters are its weight and strength to take-off under normal locust performance parameters fashion. Computational Fluid Dynamics (CFD) simulations are carried out at angles of attack of 10°, 20° and 30° and flapping frequencies of 19 Hz, 24 Hz, 30 Hz, 35 Hz and 40 Hz to investigate the aerodynamic performance of this designed MAV and optimize its flapping frequency. The simulation results defined the frequency at which the MAV is capable of hovering and take-off. In addition, the simulation results showed that the MAV is able to utilize some lift enhancement mechanisms that are being actually used by insects. These results enhances the manufacturing process of future MAV's, especially in the material selection and manufacturing method, and the transmission mechanism for flight.

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1. Introduction

Unmanned aerial vehicles (UAV) have been developed, according to Mueller [24] and Avadhanula et al. [3], as early as World War I. Their initial role was to be guided munitions that later expanded into radio controlled target drones, glide bombs, and reconnaissance aircraft. In 1936 the first radio controlled (RC) aircraft took its first flight in Germany [25]. This paved the way for RC hobbyists to reduce the size of UAVs to even smaller dimensions.

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The military had no interest in the subject of small UAVs since, as stated in Anderson et al. [2]: *they had no meaningful payloads small enough to be carried by such small vehicles*. Later, due to the rise of Micro Electromechanical Systems (MEMS) technology, they were able to develop micro scale sensors which enabled them to work with smaller aerial vehicles. Their establishments were able to develop pilot-less surveillance aircraft which were dubbed UAVs and came with obvious advantages of; (1) being able to operate in places that are considered too dangerous for humans, and (2) are generally harder to detect than normal manned aircraft [1].

Nowadays, thanks to the availability of small powerful computers, UAVs can be made *smart* enough to operate on its own. Further advancements in miniaturisation have prompted researchers to developing even smaller UAVs. According to Alexander [1], research on Micro Air Vehicles (MAVs) has been greatly supported by the U.S. Department of Defence with the goal of manufacturing insect-scaled autonomous flying aircrafts. MAVs are centimetre-scaled flying machines with potentially many possible applications in both commercial and military purposes. This includes search and rescue, hazardous environment and planetary

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explorations, surveillance and reconnaissance, sensor distribution and pollination [14].

However, their characteristic size requirements have forced researchers to revert back to the basics of developing all components from scratch since no *off-the-shelf* mechanisms, sensors, or computational equipments were available. The real research in MAVs began in 1997 when the United States Defence Advanced Research Projects Agency (DARPA) announced its *Micro Air Vehicle* programme [18]. They defined the vehicle as being less than 15 cm in each dimension (length, width, and height), having a peak velocity of 13 m s^{-1} , operational range of 10 km, and an operational time limit of more than 20 min.

Since then, many MAV prototypes have been developed including the *Entomopter*, which is being considered for a planetary exploration mission on Mars [17]. The Black Widow of this prototype was built by AeroVironment as the world's first operating MAV system [7]. In 2005, DARPA announced a similar project called *Nano Air Vehicle* programme [18]. This defined the vehicle as being less than 7.5 cm in each dimension, weighing less than 10 g, and be able to fly a distance of more than 1.0 km. The Nano Hummingbird that made by AeroVironment under a DARPA sponsored research contract was capable of indoor and outdoor operations. Recently, it was able to meet all, and exceed many, of the requirements on the phase II technical milestones set out by DARPA [7]. The Black Hornet Nano, made by Prox Dynamics of Norway, has been extensively used by NATO forces for combat operations [5]. Likewise, the Delfly Micro, which was the third ornithopter prototype of TU Delft University's Delfly project [6].

Other researchers went about creating even smaller aerial vehicles called *Pico Air Vehicles* (PAV). In 2011, Wood et al. [35], presented a model of PAV as having a maximum dimension of 5 cm and a maximum weight of 0.5 g [36]. The requirements of these models, at that time, were acceptable because their specifications were within the range of most flying insects [12,11]. Some examples of PAVs models, include the Micromechanical Flying Insect (MFI) created at the University of California Berkeley, are shown in Fig. 1. Their goal was to fabricate a centimetre-scaled electromechanical device mimicking a blowfly with complex behaviour and autonomous flight capabilities [8,9]. Another prototype from these PAVs called *Robobee*, was created by Biomimetic Millisystems Lab at Harvard University. Their goal was to develop a swarm of this autonomous insect-scale flapping-wing micro air vehicles that would resemble a bee and can be used for crop pollination [33]. Although they have been subcategorised into three separate groups, the commonly used term to calling these vehicles is still

micro air vehicles (MAVs), therefore, this will be the term used in this investigation.

Many flapping-wing MAVs have been developed since DARPA announced their MAV and NAV programs. Fig. 2 shows some of the characteristic wing span and weight of some of these existing MAVs. Some of these include the MFI (a) which was made in UC Berkeley using parallel mechanisms and piezoelectric actuators [13] and the others include the Delfly versions (b), which were made in Technical University of Delft [6].

The same approach was later followed for Robobee from Harvard which became the first insect-scale MAV that was able to generate enough thrust to lift its own weight. Piezoelectric actuators were also used by a group of researchers at the University of Vanderbilt as part of a tuned resonant drive for a two winged MAV. A different approach was used for the 50 g *Entomopter* using reciprocating chemical muscles [23]. A butterfly mimicking MAV made in University of Tokyo weighs 400 mg and has a wingspan of 14 cm. An RC Flapping wing MAV was created by AeroVironment called *eMicrobat*, which is based on Mamalian flight [10]. To the best of authors' knowledge, there is no previously published work reported on the MAV mimicking a real locust.

The aim of this study is to design and manufacture a flapping wing micro air vehicle. The aerodynamic performance of this flapping-wing MAV can mimic the movement and appearance of a flying locust insect. We use here the Computational Fluid Dynamics (CFD) approach to simulate the movement of this MAV. The machine is mainly designed according to the natural design of the insect. In essence, it must use the same mode of flight (i.e. flapping-wing), be within the same sizing range of the insect, and resemble a similar colour pattern, and outer structure.

This paper is organized as follows. Section 2 describes the efforts that the researchers followed to design an inspired insect-scale MAV. Section 3 introduces the background theory behind the design and investigation of MAV's. Section 4 describes the design methods, transmission systems and components' specifications of the current MAV. Section 5 then combines the results from both experimental numerical approaches and compare with previous published work on similar MAV model. Finally, Section 6 presents our conclusions.

2. Insect-scale flapping-wing MAVs

Researchers made many technological leaps for generating a biologically-inspired insect-scale MAV since 1998. These include

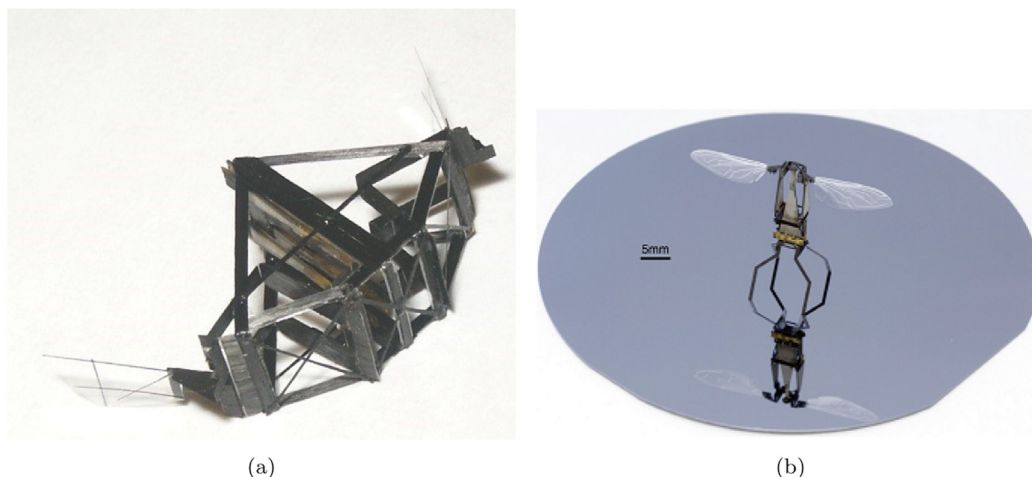


Fig. 1. Examples of Pico Air Vehicles; (a) MFI [31], (b) Robobee [35].

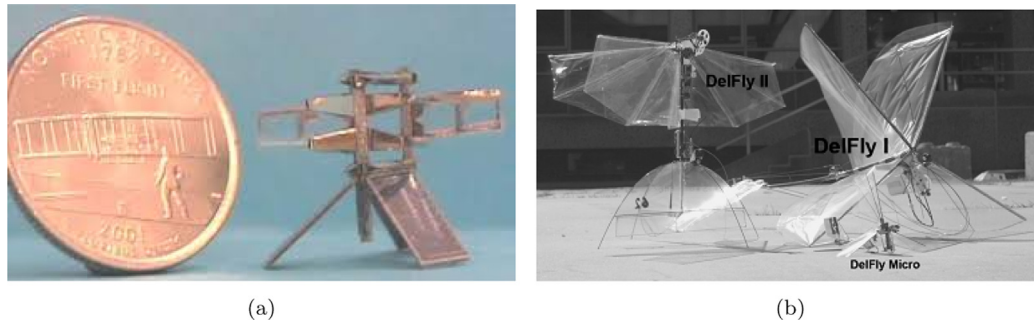


Fig. 2. Wing span and weight Characteristics of Existing MAVs, (a) MFI (10 mm–25 mm span), (b) DelFly I (50 cm span, 21 g), DelFly II (28 cm span, 16.07 g) and DelFly Micro (10 cm span, 3.07 g).

piezoelectric bending actuators [30] and its optimization [37] for the actuation motion, and manufacturing methods for use on composite materials [34]. Several designs were made by different researchers, the main specifications used were mass, wing span flapping frequency, stroke amplitude and rotation angle. Wood et al. [37] described the piezoelectric actuator used by UC Berkeley, for their micro flying insect. The 10 mm long bimorph actuator consisting of a flexural carbon fibre layer sandwiched in-between two PZT-5H piezoelectric materials for the normal length, and s-glass at the tip length. This was able to create up to 250 m tip deflection, provide 123 mN of blocking force, weigh 10 mg, operate at 200 Hz frequency, and produce more than 300 W kg^{-1} of energy density.

According to Wood et al. [37], these parameters are similar to high performance DC batteries. Several researchers also investigated the materials used for the flapping wings. Mostly issuing Smart Composite Microstructures fabrication technology to construct the wings from composite material that can provide flexural joints such as polyimide polymer, or kapton, sheet sandwiched in-between two sheets of cured carbon fibres. Several modifications and additions were used to the design and the manufacturing process which were aimed at improving the controllability and flight of the flapping MAV's [15,16]. Anderson et al. [2] indicated that the main challenges facing the flapping MAV's are; micro-fabrication; stability characterization and control; designing for highly coupled fluid structure interactions; and predicting the low Reynolds number and unsteady aerodynamics.

3. Background theory

Two contradicting views as to whether flapping wings create lift and thrust simultaneously [29], or only thrust and lift is generated passively as a by-product [1]. There are several unsteady aerodynamic mechanisms, as stated by Shyy et al. [29], that are associated with flapping wing aerodynamics for force generation. These include: Clap-and-fling mechanisms; Delayed stall of the leading edge vortex (LEV); Downward jet in the wake region; Lift peak due to rapid pitch-up rotation; Tip vortex; Wake capture due to interactions between the aerofoil and vertical flow [22]. The lift production of the wings is affected by several characteristics. One of which is the aspect ratio, which, according to Alexander [1], is the ratio of the wingspan to the average chord. This greatly affects the tip vortices on the wings. A short and broad wing has a low aspect ratio, whereas, a long and slender wing has a high aspect ratio.

The lift and drag coefficients, and stalling behaviour of the wings will depend on maximum thickness location, flatness or curvature of the lower surface, blunt or droopiness of the leading edge, and sharpness of the taper towards the trailing edge. Experiments conducted by Okamoto et al. [26] on the effects of aerofoil thickness showed that the aerodynamic characteristics of the wings decreases as the thickness increases. Flapping wing performance

is also influenced by the weight of the wings relative to the total insect weight. Other wing characteristic that affects its lift production is the rotational speed. A small increase in the speed of the wing, thus, higher flapping frequency, results in a large increase in lift. These findings have been obtained from the wind tunnel tests [27,32] and CFD approaches [21,19] that have been used extensively to study the flow characteristics and aerodynamic performance of different models of flapping wings micro aerial vehicles.

4. Design, materials and methods

The main manufacturing method used for the design in this study is the 3D printing. The MakerBot Replicator 2 Desktop 3D Printer is capable of printing layers up to 100 m resolution; therefore, all components used in this study are constrained by this dimension. The approach taken for the design is to use the size of an actual adult locust whilst keeping the design within the maximum MAV dimension 15 cm specified by DARPA. Based on a

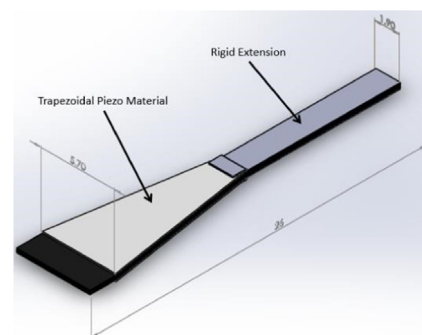


Fig. 3. Resulting piezoelectric actuator design using geometry enhancement method.

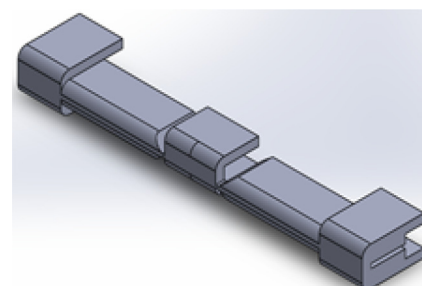


Fig. 4. SolidWorks model of the thorax kinematics transmission system.

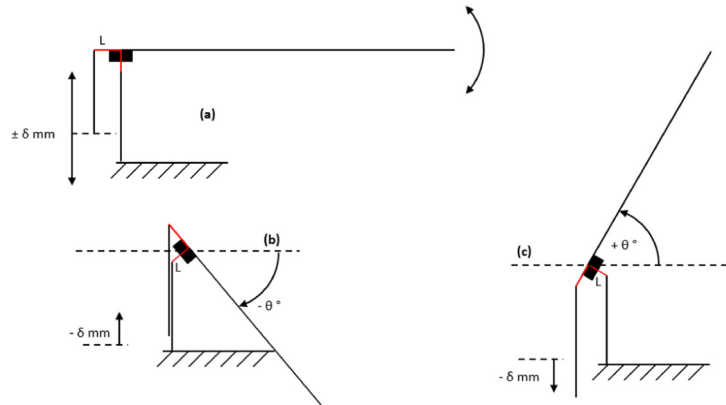


Fig. 5. Thorax kinematics transmission system design 1; (a) stationary position; (b) maximum positive deflection; (c) maximum negative deflection.

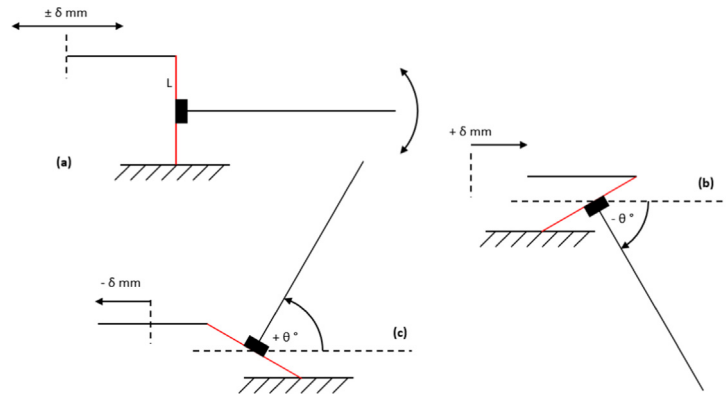


Fig. 6. Thorax kinematics transmission system design 2; (a) stationary position; (b) maximum positive deflection; (c) maximum negative deflection.

report published by the National Geospatial-Intelligence Agency [28], an adult sized locust has an average body length of 60 mm and wingspan of 120 mm, which are acceptable since they are within the maximum dimensions.

Since that the aim here is to design an insect-scale, this study is focused on the MFI, Robobee, and AFIT MAV. In addition, all these three models are initially designed for vertical take-off and hover. Therefore, these models were used as the basis for the current design. The actuator is the main source for the flapping wing

motion. The most desirable specification for an actuator is, based on Anderson et al. [2], its power density that is given by the following equation

$$PD = \frac{f_B \cdot \delta \cdot \omega_n}{M} \quad (1)$$

where PD is the power density, f_B is the blocking force, δ is the Actuator deflection, ω_n is the flapping frequency, and M is the actuator mass.

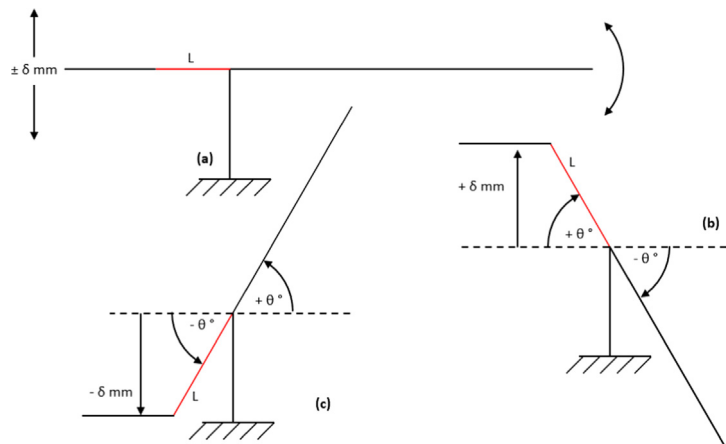


Fig. 7. Thorax kinematics transmission system design 3; (a) stationary position; (b) maximum positive deflection; (c) maximum negative deflection.

Table 1
Calculation results for the shortest link.

Parameters	Values
Tip deflection	$\pm 1400 \mu\text{m}$
Stroke amplitude	$\pm 55^\circ$
Shortest link	1.709084 mm

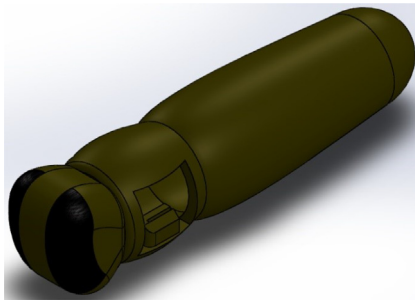


Fig. 8. The SolidWorks model of the MAV fuselage.

Improvements by geometrical method are achieved by using a trapezoidal shape, rather than the traditional rectangular actuator, and an additional rigid extension. This provides more materials at the clamped end, where bending moment will be highest, and less at the tip, and the rigid extension increases the actuator deflection. Fig. 3 illustrates the CAD geometry of the trapezoidal actuator fixed with the additional rigid extension part. As shown in Fig. 3, the dimensions of the trapezium parallel sides are 1.9 mm and 5.7 mm, however the total length of actuator is 25 mm.

There was a variety of methods proposed on how the actuators will transfer the actuator deflection motion to the flapping motion of the wings. In the current design, the deflection motion is done by having a *shortest link* (L) in between the wing structure and the actuator.

The actuator deflection will cause the short link to rotate based on the desired flapping wing angle. With the link being fixed to the

Table 2
Mass summary of the manufactured design.

Component	Mass (g)
Fuselage	3
Wings (both)	1.4
Kinematics Transmission System	0.7
Actuators	1.0
Total	6.1

wing structure, its rotation will be transferred to the wings, thus, achieving the desired stroke amplitude. For the thorax kinematics transmission system, three designs were investigated. Fig. 4 shows the SolidWorks model of the transmission system design.

Figs. 5–7 show three different designs of the transmission systems used in the current novel MAV. The third design shown in Fig. 7 has the lightest weight compared to the other designs (see Figs. 5 and 6) and was easy to assemble since it had the least number of components. Therefore, the third design is chosen for the kinematics transmission system. The shortest link is determined by using basic trigonometry with the result shown in Table 1.

Designing the wings and fuselage structures required borrowing dimensions off an actual insect. According to the report of the National Geospatial-Intelligence Agency [28], an adult sized locust has an average wingspan of 120 mm and body length of 60 mm. These values were acceptable since they are within the maximum dimensions defined by DARPA. The fuselage (i.e. the head and body of the MAV) was designed based on shape observations on images of locust insects. Fig. 8 shows the fuselage model of the current novel MAV.

For wing design, the method of sweeping the leading edge of a wing design forward is implemented in SolidWorks to increase the surface area without increasing the maximum chord and thus, increasing the overall lift generation [20,4]. Fig. 9 shows the SolidWorks design of the current MAV wing design.

Fig. 10 shows the printed parts and the complete assembly of the current novel MAV. All parts were assembled together using spray adhesive. Table 2 illustrate the mass breakdown of each

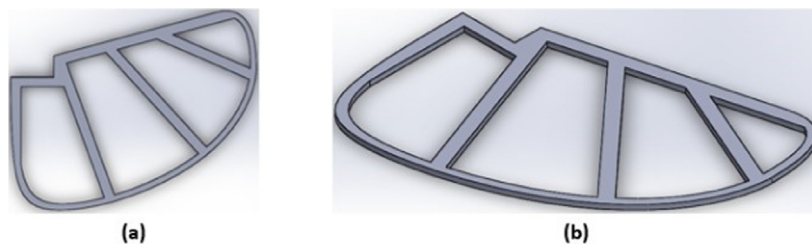


Fig. 9. MAV wing design; (a) top view and (b) isometric view.

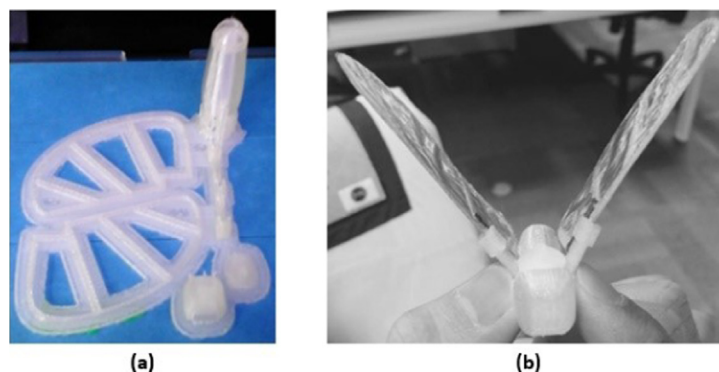
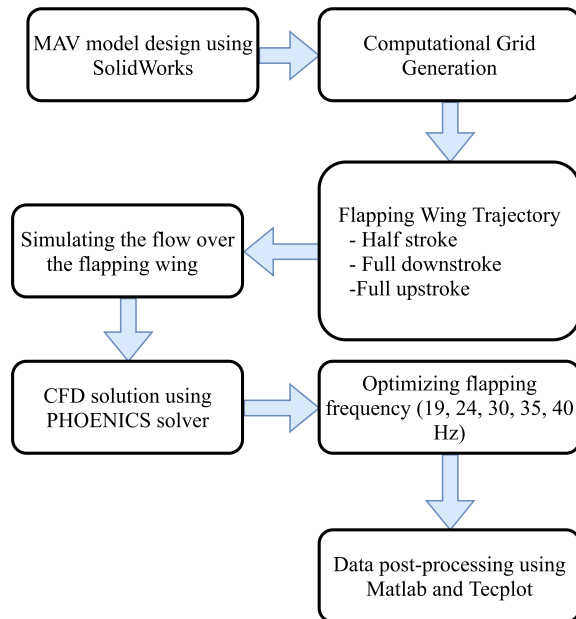


Fig. 10. A photograph of (a) 3D printed parts and (b) complete assembly of MAV.

Table 3

Frequency at which the lift generated is capable of lifting.

Frequency	Maximum lift	Liftable mass for both wings	Total mass ratio	Flying Capability
19 Hz	13 mN	1.85 g	30%	-
24 Hz	15.7 mN	3.2 g	53%	-
30 Hz	21.5 mN	9.69 g	81%	-
35 Hz	46 mN	13.62 g	113.5%	Hovering
40 Hz	60 mN	18.79 g	146.5%	Take-off and Hovering

**Fig. 11.** Flow chart for CFD analysis of current MAV model.

component used in the final MAV desing. The total mass of the current MAV is 6.1 g, as show in Table 2.

5. Results and discussion

5.1. Lift at normal flapping frequency

Numerical and experimental results are obtained using numerical simulations. The CFD PHOENICS package is adopted to quantify the ability of the design to create lift and the associated vortices.

The low-Reynolds-number mixing-length model is used to simulate the flapping motion of the wings during flight. Several attempts are made to investigate the frequency required to lift the total mass of the designed MAV. Table 3 shows the frequency at which the lift generated by the current MAV is capable of lifting.

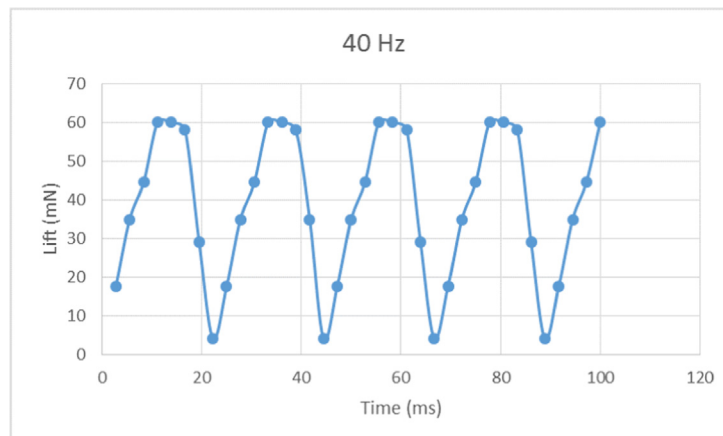
The procedures implemented for this study that summarize the research methodology are as shown in the flow chart given in Fig. 11.

Fig. 12 shows the lift values at actuation frequency of 40 Hz. From this, it can be seen that at 30 Hz frequency, one wing is able to generate a maximum lift of roughly 60 mN and can generate an average lifting force of 43 mN. This shows that at 35 Hz, both wings are able to lift a total mass of 18.79 g or 146.6% of its overall weight. This indicates that the current MAV would be able to take off at this frequency. This result is similar to occurring pattern as the ones obtained by Avadhanula et al. [3] on their work on the MFI, as shown in Fig. 13.

5.2. Aerodynamic lift mechanisms

Simulation results show that a wake vortex is being created by the wing, as shown in Fig. 14. This suggests that the current designed MAV may have the capabilities of utilising wake capture mechanism for increasing lift at each flapping stroke. In addition, leading edge (LEV) and trailing edge (TEV) vortices are also created, which indicates that the MAV could be capable of using other varieties of lift enhancement mechanisms. The leading edge vortex can be seen as increasing in size as the angle of attack increases, whereas, the wake is decreasing in size.

Figs. 15–18 show the stream lines occurring around the novel MAV model. From these figure, it can be seen that the tip vortices are being created at both ends of the MAV, which are interacting with the LEV shed (see Figs. 16 and 17). This indicates that the MAV is also capable of utilising lift enhancement mechanism by way of tip vortex. In addition, the tip vortices are also seen to be

**Fig. 12.** Lift values over 100 ms at 40 Hz for one MAV wing.

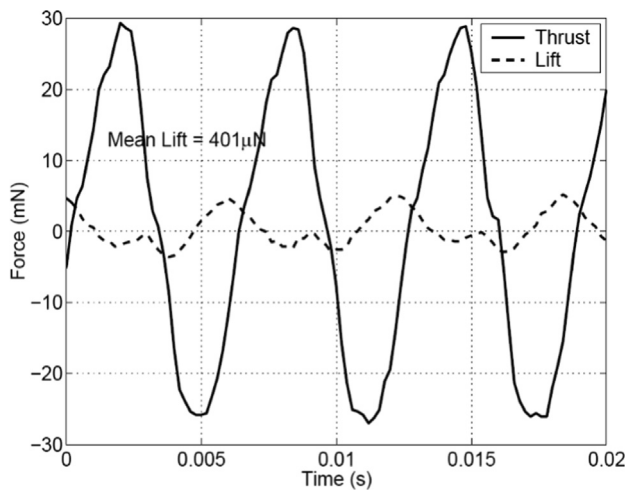


Fig. 13. Measured lift values for the UC Berkeley MFI [3].

interacting with the wake, which further imply that the MAV is utilising tip vortex mechanisms in more methods than one.

Figs. 19 and 20 show the vortices at maximum upward stroke and maximum downward stroke of the MAV model. From this it can be seen that no bound vortex is being produced by the MAV, therefore, it is incapable of utilising clap-and-fling mechanism to increase its lift to negate the Wagner effect. This was due to the maximum chosen upward stroke angle, which prevented the wings from coordinating a clapping motion and, thus, the flinging motion to increase its lift.

In addition, vortices are occurring near the maximum up and down strokes, thus, further suggesting that the wings are using wake capture mechanism to increase the overall lift. Note that at the upstroke the vortices at underneath the MAV have much higher velocity than the vortices at the top since the former is a recently made wake vortex, whereas, the latter is has been used by the wings to effectively increase the flow velocity around the wings to generate a second force peak. A frontal view of the main vortex created by the flapping of the wings could be seen in Fig. 20.

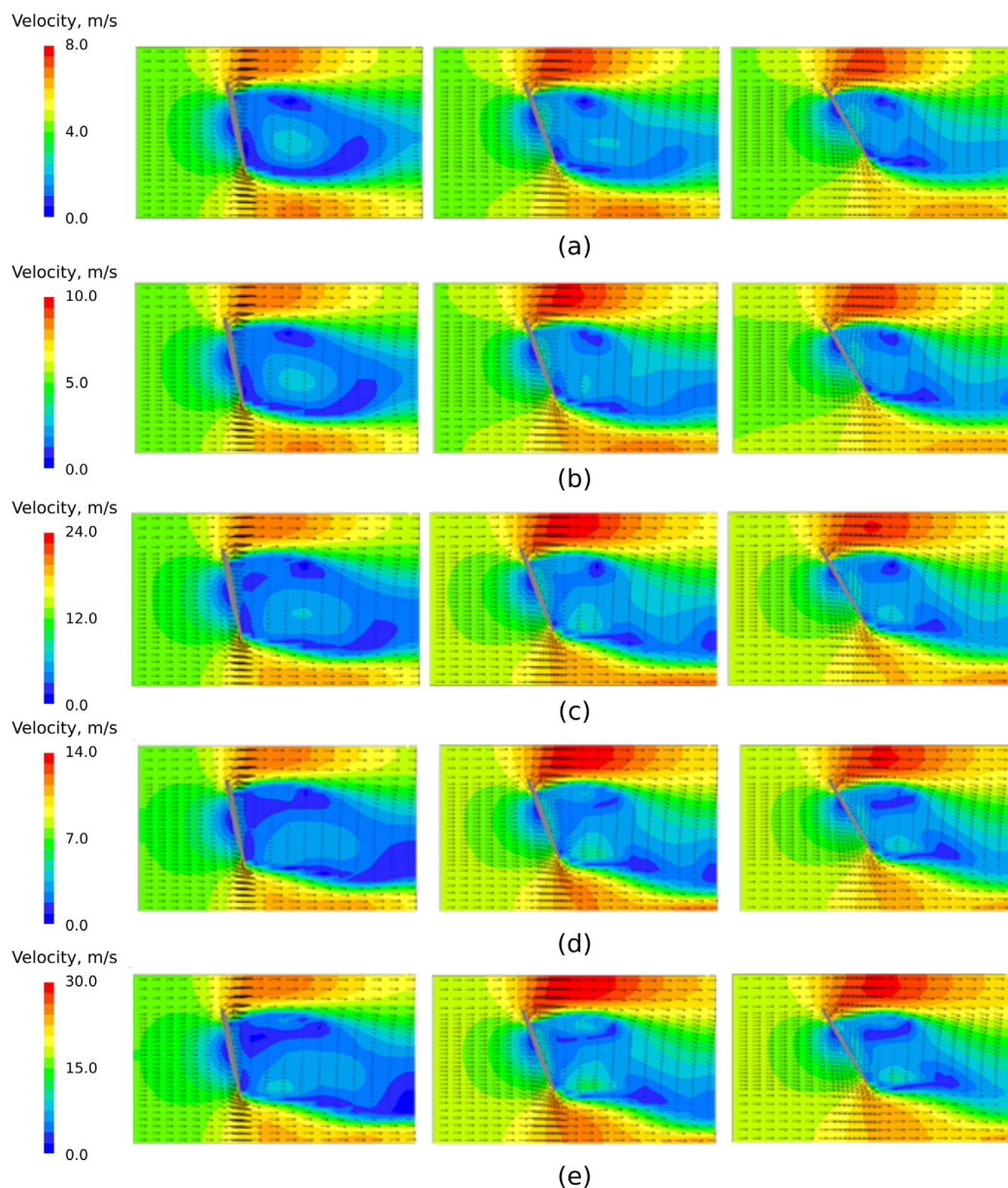


Fig. 14. LEV and TEV patterns at 10°, 20°, and 30° AoA, respectively, at (a) 19 Hz, (b) 24 Hz, (c) 30 Hz, (d) 35 Hz, and (e) 40 Hz.

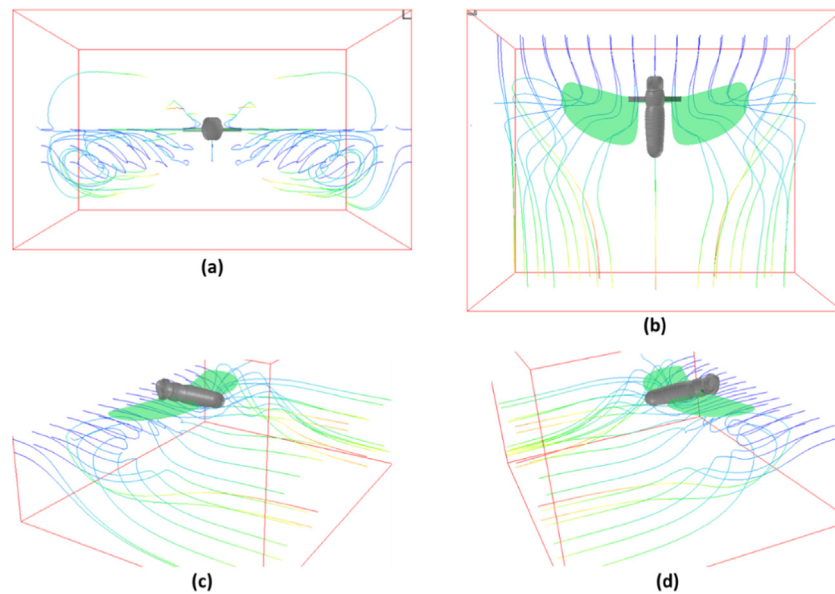


Fig. 15. Flow patterns under MAV during half stroke at different views; (a) front; (b) top; (c) left 3d; (d) right 3d.

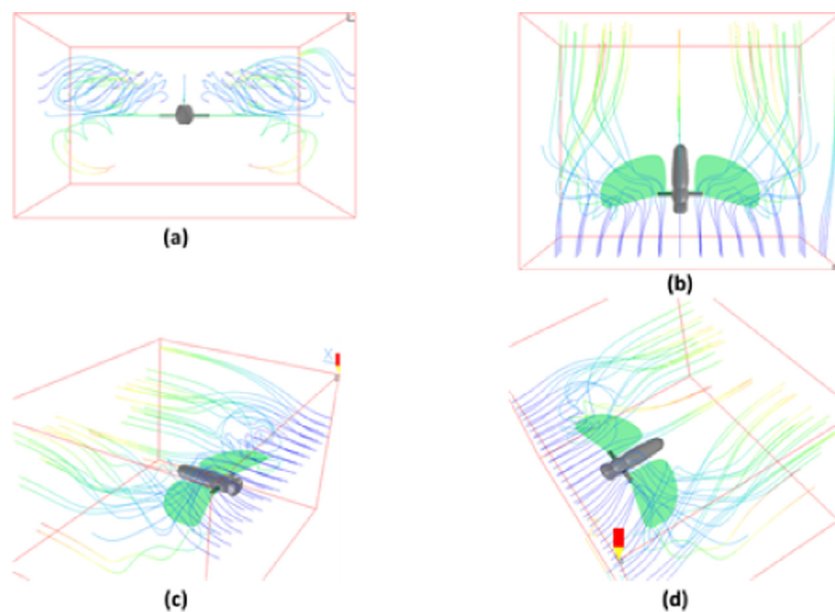


Fig. 16. Flow patterns under the MAV during half stroke at different views; (a) front; (b) top; (c) right 3d; (d) left 3d.

The current MAV was compared to other flapping wing MAVs, as shown in Fig. 21. It currently fits within the trend line, thus, further suggesting it is capable of flight under the correct flapping frequency.

6. Conclusion

The aim of this research was to design an insect-scale novel MAV that can mimic a locust with the basis of concentrating on its aerodynamic performance. From the novel results it was found that the designed MAV was capable of lifting its own weight at a frequency higher than 35 Hz. Moreover, it was noted that at flapping frequencies around 35 Hz the MAV will be able to hover,

whilst at 40 Hz or higher, successful take-off will be achieved. Furthermore, based on the CFD simulations conducted, the MAV was able to utilise a few lift enhancement mechanisms that enabled it to increase its lift. Therefore, the aerodynamics performance of the MAV's that mimicking locust is much better than the traditional types that mimicking dragonfly and birds. Comparison of the current MAV with other flapping wing MAVs, showed that it fits within the trend line. This means that it is capable of flight under the correct appropriate flapping frequency.

These findings provide the following insights for future research: (1) studies need to be carried out in order to enhance the manufacturing process, especially the material properties and manufacturing method, (2) further research is required to deter-

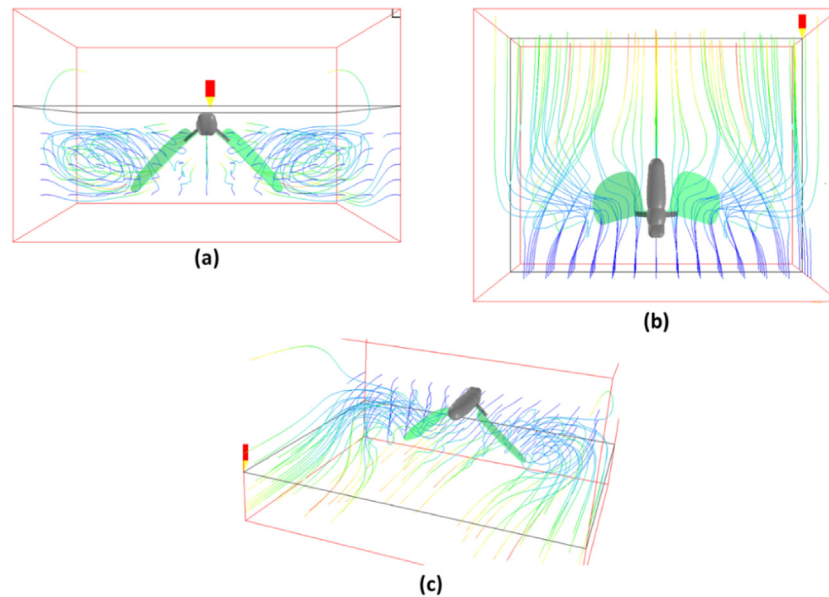


Fig. 17. Flow patterns under the MAV during full down stroke at different views; (a) front; (b) top; and (c) 3d.

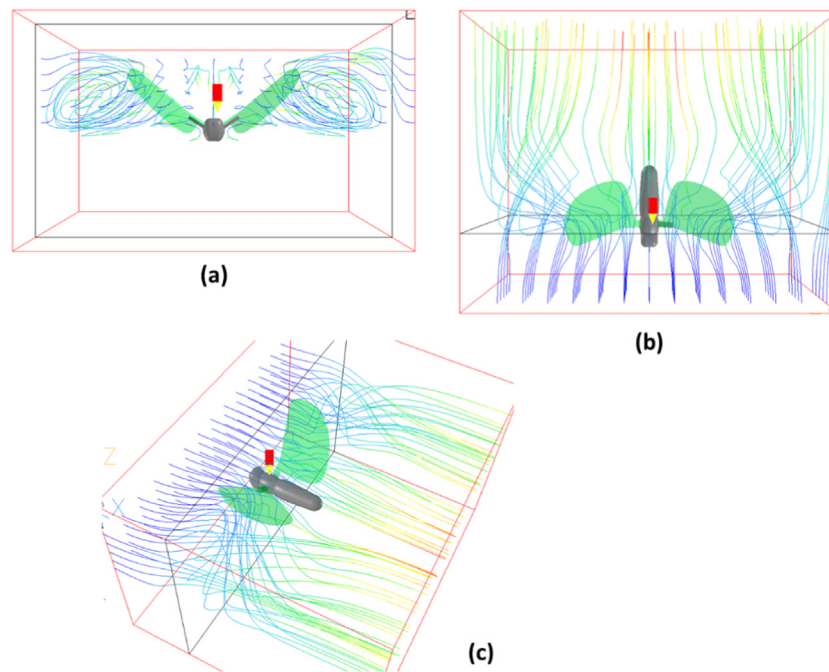


Fig. 18. Flow patterns above the MAV during full up stroke at different views; (a) front; (b) top; and (c) 3d.

mine the elasticity of the components and its vulnerability to damage as well as quantifying and prevent any human errors, and (3) experiments, using a broader range of MAV, could shed more light on remanufacturing the MAV prototype and using different adhesive for the transmission mechanism for test flight, in order to verify the results.

Author Contributions

Conceptualization, T.M, M.A.M, R.S; Data curation, T.M, M.A.M, R.S, M.H.S, M.F.C; Formal analysis, M.A.M, R.S, M.H.S, T.M; Funding

acquisition, M.A.M, R.S, T.M; Investigation, T.M, M.A.M, R.S, M.H.S, M.F.C; Methodology, M.A.M, R.S; Project administration, M.A.M, R.S, T.M; Resources, M.A.M, R.S, M.H.S, M.F.C; Software, T.M, M.A.M, R.S; Supervision, T.M, M.A.M, R.S; Validation, T.M, M.A.M, R.S, M.H.S, M.F.C; Visualization, T.M, M.A.M, R.S, M.H.S, M.F.C; Writing original draft, T.M, M.A.M, R.S, M.H.S, M.F.C; Writing review and editing, M.A.M, M.H.S, M.F.C.

Declaration of Competing Interest

The authors declare no conflict of interest.

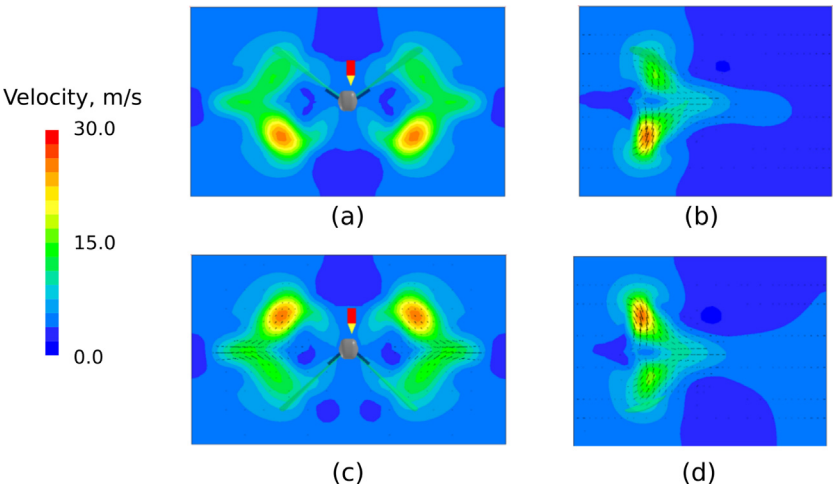


Fig. 19. Vortices at; (a) maximum upstroke front view; (b) maximum upstroke side view; (c) maximum downstroke front view and (d) maximum downstroke side view.

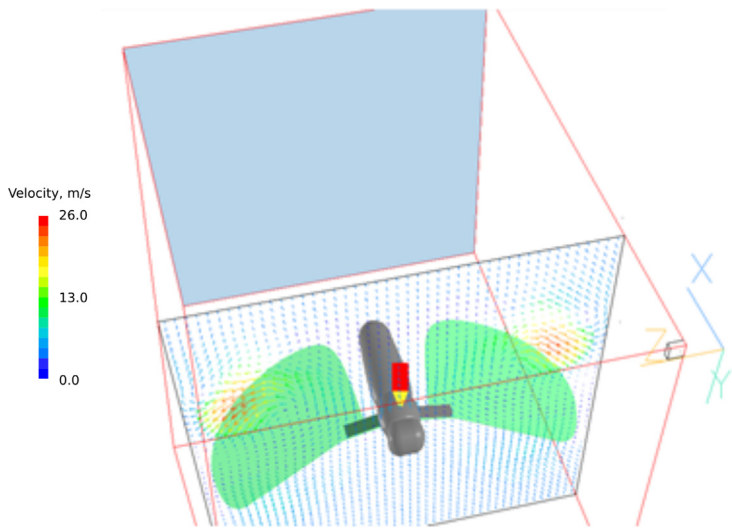


Fig. 20. Frontal view of the flapping wing vortex.

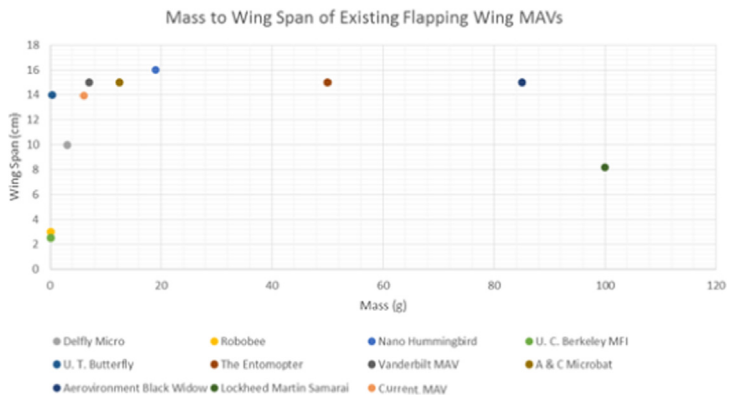


Fig. 21. Comparison of existing flapping wing MAV and the current designed MAV.

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